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(54) Method and apparatus for analyzing process characteristics.

(57) Methods and apparatus for determining characteristics of a process — such as primary and second time constants, dead-time, and gain — apply a doublet pulse to the process and measure its response. By way of example, in one aspect there is provided a method for generating a signal, τ_1, representing an estimate of a primary time constant of a non-self-regulating process, in accord with the mathematical expression τ_1 $(\delta m \tau_a{}^2)/A^+$; where A^+ is a factor representing the time-wise integration of the controlled variable during the period when the doublet pulse is being applied.

EP 0 572 245 A2

This application is related to the following copending, commonly assigned applications, assigned to the assignee hereof and filed the same day herewith, and which claim priority from United States Patent Application No. 889474 entitled METHOD AND APPARATUS FOR TUNING PROCESS CONTROL EQUIPMENT (Attorney Docket No. 10226), and United States Patent Application No. 889473 entitled IMPROVED METHOD AND APPARATUS FOR ADAPTIVE DEAD TIME PROCESS CONTROL (Attorney Docket No. 10228).

The teachings of the above-cited applications are incorporated herein by reference.

Background of the Invention

The invention relates to process control and, more particularly, to systems for analyzing processes to determine characteristics such as dead time, primary and secondary time constants and static gain.

Process control refers to a methodology for controlling the operational parameters of a process by monitoring one or more of its characteristics over time. It is used to ensure that the quality and efficiency of a process do not vary substantially during a single run or over the course of several runs. While process control is typically employed in the manufacturing sector, it also has application in service industries.

A process control unit, or "controller," typically operates by comparing values of a process characteristic -- referred to as the controlled variable -- with a target value to determine whether the process is operating within acceptable bounds. For example, in a process in which fluid flows at a constant rate from a tank that is continuously filled to constant volume, a controller monitors the liquid level and, if necessary to prevent the tank from running dry or overflowing, adjusts an inlet valve to increase or restrict inflow to the tank.

In order to function properly, a controller must be adjusted to accommodate charcteristics of the specific process it will control. This requires identifying process parameters such as the primary time constant (which reflects the rate at which the process responds to changes in input), gain (which reflects the magnitude of response), and so forth.

Prior art techniques for identifying those parameters involve applying a single step to the process, monitoring the process response and, from that calculating the requisite process parameters.

For example, in a text previously authored by him, the inventor hereof suggests the following procedure for determining process dead time:

1. Place the process controller in manual mode and apply a single step to the process.
2. Monitor th resultant change in output of the proc ss.
3. Graphically, or oth rwise, determine th point of intersection b tween (a) the line d fining process output prior t application of the step pulse, and (b) the tang nt of maximum slope of the process respons curve.

The point of intersection identified in step 3 is taken as the dead time.

This and related techniques for determining process characteristics by monitoring response to a single step are generally quite effective. Nevertheless, an object of this invention is to provide more accurate methods and apparatus for analyzing process characteristics.

More particularly, an object of this invention is to provide a method and apparatus for determining process characteristics such as primary and secondary time constants, dead time, and steady state gain, among others, as effectively and accurately as possible.

Summary of the Invention

The invention achieves the aforementioned objects by providing methods for determining characteristics of a process by applying a doublet pulse to the process and by measuring its response. Those characteristics include primary and second time constants, dead time, and gain. The invention is applicable, for example, in determining characteristics of a process that is to be placed under the control of a process controller. Moreover, the analysis can b carried out by, or in connection with, the controller itself, as adapted in accord with the teachings herein.

The doublet pulse can be applied to the process by the manipulated variable signal output of the controller in accord with the following steps: (i) incrementing the manipulated variable a predetermined amount, δm; (ii) monitoring the controlled variable to determine the time period, τ_a, for it to change from its original value by an amount, NB; (iii) once the controlled variable has changed by that amount, decrementing the manipulated variable stepwise by an amount $-2 \times \delta m$; (iv) after another time interval τ_a, incrementing the manipulated variable an amount δm to bring it to its original value.

Aspects of the invention pertain to methods for determining characteristics of non-self-regulating processes, i.e., those which have no natural equilibrium or steady state. A simple example of such process is shown in Figure 1a. There, a metering pump 10 removes a constant flow of fluid from a tank 12, whil inflow to the tank is controlled by valve 14. If the inflow varies from the outflow, then the tank will eventually overfill or run dry.

In one aspect, the invention provides a method for generating a signal, τ_1, representing an estimate of a primary time constant of a non-self-regulating process. The primary time constant of a non-self regulating process is th tim it tak s for th output (th

controlled variable) to change an amount qual to th step chang in its input (th manipulated variabl).

According to this aspect of th invention, that signal is generat d in accord with the mathematical expression

$$\tau_1 = (\delta m \tau_a^2)/A^+$$

where A^+ is a factor representing the time-wise integration of the controlled variable during the period when the doublet pulse is being applied.

For a first-order non-self-regulating process -- that is, a process that can be modeled by a first-order differential equation -- the invention provides a method for generating a signal, τ_d, representing a dead time of the process. The dead time is the time it takes a change in the process input (i.e., the manipulated variable signal) to be reflected by a change in the controlled variable signal. For example, referring to Figure 1a if the flow of fluid delivered from the tank is to be delivered at a specific temperature, based on heat delivered by a heater 16 and measured at the pump 10, then the dead time is the time it takes a change in temperature of the fluid to be detected at a temperature sensor.

According to this aspect of the invention, the dead time signal τ_d is generated in accord with the mathematical expression

$$\tau_d = \tau_a - (NB\tau_1/\delta m)$$

For a non-self-regulating process of the second-order, the invention provides a method for generating the signal τ_d by the following steps:

(i) generating a signal, t_1, representing a first time interval as a function of the mathematical expression

$$t_1 = NB * \tau_1/|\delta m|$$

(ii) generating a signal, t_2, representing a second time interval having, initially, a value substantially equal to that of the first time interval, t_1;

(iii) iteratively regenerating the signal, t_2, until its value no longer changes significantly between iterations; wherein, such regeneration is in accord with the mathematical expression

$$t_2 = t_1 + \tau_2 * (1 - e^{-t_2/\tau_2});$$

where τ_2 is a secondary time constant of the process as determined in accord with other aspects of the invention, as described below; and

(iv) estimating the dead time τ_d as a function of the mathematical expression

$$\tau_d = \tau_a - t_2$$

where t_2 is a final value of that interval, as determined in step (iii), above.

Other aspects of the invention pertain to methods for determining characteristics of self-regulating processes, i.e., those which have a natural tendency to return to a natural equilibrium or steady state. According to one aspect, the invention provides a m thod for g nerating a signal, τ_1, estimating the primary time constant of a self-regulating process. This is bas d on evaluation f th math matical expression

$$\tau_1 = \tau_a/\ln(1 - OVS)$$

where OVS is a ratio between first and second peak values of the controlled variabl during application of th doublet puls .

Anoth r aspect provid s a m thod for gen rating a signal, K_p, representing a steady-state gain of a first-order self-regulating process, as a function of th mathematical expression

$$K_p = \delta c_1/(\delta m * OVS)$$

where δc_1 represents a difference between the original value of the controlled variable and its first peak value during application of the doublet pulse.

Still other aspects of the invention provide apparatus operating in accord with the above methodology. These and other aspects of the invention will become evident from the following description which is given by way of example only with reference to the attached drawings, in which:

Figure 1a depicts an exemplary process of the type amenable to analysis in a method according to the invention;

Figure 1b illustrates the process of Figure 1a coupled to an apparatus according to the invention for determining the characteristics of that process;

Figure 2 depicts a preferred structure of an apparatus for determining process characteristics constructed in accord with the invention;

Figure 3 depicts a preferred method for determining process characteristics in accord with the invention; and

Figures 4 - 6 depict doublet pulses and their effect on first-order non-self-regulating, second-order non-self-regulating, and first-order self-regulating processes.

Detailed Description of the Illustrated Embodiment

Figure 1b depicts an exemplary process of th type amenable to analysis by an apparatus constructed and operated in accord with the invention. As above, a metering pump 10' is designed to deliv r a constant flow of fluid 11' from tank 12'. Inflow to th tank is controlled at valve 14'.

A process controller 18 monitors the level of fluid in the tank 12' and controls the inflow at valve 14'. More particularly, the controller monitors a controll d variable signal, c, representing the level of fluid in the tank. The controller generates a manipulated variabl signal, m, that governs the degree of flow through th valve 14'.

The illustrated process is exemplary only and represents any process amenable to analysis in accord with the teachings herein. Moreover, the manipulated and control variabl signals, m and c, respectively, can b generated in a conv ntional manner appropriate t the process under analysis.

Figure 2 depicts an apparatus 20 for determining

process characteristics constructed in accord with the inv ntion. The apparatus includes a controlled variabl signal monitor 22, an el ment 24 for generating the manipulated variabl signal, an element 26 for generating a doublet pulse, and elements 28, 30, 32, 34 for estimating time constants τ_1, τ_2, τ_d, and K_p, respectively. The elements 22 - 34 are interconnected and operated in the manner described below.

The monitor 22 monitors, or samples, values of the controlled variable c at intervals δt in a conventional manner, e.g., under control of a timer or clock. Preferably, the sampled values are stored in an array; alternatively, they can be stored in a file, in registers, or in other like manner.

The doublet pulse generating element 26 generates a manipulated variable signal in the form of a doublet pulse. Particularly, as illustrated in Figure 3, the element 26 increments the manipulated variable signal, m, a predetermined amount, δm. The element 26 notes changes in the controlled variable signal, c, resulting from the incrementing of manipulated variable signal, to determine the time period, τ_a, before the controlled variable signal changes from its original value by a predetermined noise band amount, NB. Once the controlled variable has changed by that amount, the element 26 decrements the manipulated variable stepwise by an amount -2 x δm. After another time interval τ_a, the element 26 increments the manipulated variable an amount δm to bring it to its original value.

Those skilled in the art will appreciate that illustrated apparatus 20, including elements 22 - 24 therein, can be implemented based on the teachings herein in special purpose hardware. Preferably, those elements are implemented in software for execution, e.g., on a general purpose microprocessor. In this regard, it will be appreciated that such implementation can be attained using conventional programming techniques as particularly adapted in accord with the teachings herein to provide the disclosed structure, signaling and functionality.

The process characteristics determined, e.g., by such an apparatus 20, in accord with the teachings herein can be used in connection with the methods and apparatus disclosed in the above-cited related patent applications.

Referring to Figure 3, an apparatus 20 according to the invention analysis proceeds according to the type and order of the process being analyzed, to wit, whether the process is self-regulating or non-self-regulating process and whether it is first-order or second-order. A determination as to type and order can be determined automatically in the manner discussed below.

Ref rring, to Figur 4 there is shown the effect of th doublet pulse on a 1st-order non-s lf-regulating process. As illustrated, th first pulse of the manipulated variable, m, drives th controll d variable c at a rate:

$$dc/dt = \delta m/\tau_1 \quad (1)$$

where τ_1 is the integrating time constant of the process.

The change in the signal c in response to the initial pulse can be represented as follows:

$$\delta c = \delta m(\tau_a)/\tau_1 \quad (2)$$

where τ_a is the width of the pulse.

The downward pulse of the manipulated variable signal drives the controlled variable signal c back to its original value in the same way, producing an integrated deviation A^+.

The element 30 generates a signal, A^+, representing the integrated deviation in accord with the mathematical relation:

$$A^+ = \delta m(\tau_a^2)/\tau_1 \quad (3)$$

From that signal, A^+, the element 30 generates a signal, τ_1, representative of an estimate of the primary time constant of the process. Particularly, it gen rates the signal, τ_1, in accord with the mathematical relation:

$$\tau_1 = \delta m(\tau_a^2)/A^+ \quad (4)$$

Based on that result, the element 28 generates a signal, τ_d, representing an estimate of the dead tim . That signal is determined by subtracting τ_a from the time required for c to reach the noise band, NB, as expressed by the following mathematical relation:

$$\tau_d = \tau_a - (NB * \tau_1/\delta m) \quad (5)$$

The apparatus 20 can determine whether a non-self-regulating process is of the first or second order by comparing the time interval τ_a with the factor $A^+/\delta c$. If those values are equal -- that is, $A^+/\delta c = \tau_a$ -- then the process is deemed to be of the first order; otherwise, it is deemed to be of the second order.

Figure 5 depicts the effect of application of a doublet pulse to a 2nd-order non-self-regulating proc ss.

At the outset, it is noted that the area under the curve A^+ is not affected by the secondary lag.

However, the secondary time constant of th process reduces the peak height δc. By monitoring that peak height, element 32 can generate a signal τ_2 representative of the secondary time constant according to the mathematical relation:

$$\tau_2 = A^+/\delta c - \tau_a \quad (6)$$

The time required for the controlled variable signal c to reach the noise-band limit, NB, is a complex function of both time constants τ_1 and τ_2. The dead time element 28 generates the signal τ_d approximating that dead time by executing the following steps:

i) computing a first time interval t_1 as a function of the mathematical expression

$$t_1 = NB * \tau_1/|\delta m|$$

ii) initializing a second time interval t_2 to have a value substantially equal to that of the first time int rval, t_1,

iii) iteratively determining the second tim interval t_2 in accord with th mathematical expression

$$t_2 = t_1 + \tau_2 * (1 - e^{-t_2/\tau_2})$$

until a difference betwe n successive iterative values of the s cond tim int rval t_2 are within a predetermined rang , and

where τ_2 is a secondary time constant of the non-self-regulating process,

iv) estimating the dead time τ_d as a function of the expression

$$\tau_d = \tau_a - t_2 \quad (7)$$

where t_2 is a final value resulting from step (iii).

Figure 6 illustrates the effect of application of a doublet pulse to a 1st-order self-regulating process. In this instance, the controlled variable overshoots its original value, resulting in an area A^+ which is compensated by an equal and opposite area A^-.

Illustrated peak, δc_1, is an exponential function of time (pulse duration), as expressed by the following mathematical relation:

$$\delta c_1 = K_p \delta m (1 - e^{-\tau_f/\tau_1}) \quad (8)$$

where K_p is the process steady-state gain.

The height of the second peak, δc_2, can be expressed by the mathematical relation:

$$\delta c_2 = - K_p \delta m (1 - e^{-\tau_f/\tau_1})^2 \quad (9)$$

The overshoot is the ratio of the first and second peaks, δc_1 and δc_2, expressed as follows

$$OVS = - \delta c_2/\delta c_1 = 1 - e^{-\tau_f/\tau_1} \quad (10)$$

Accordingly, for a self-regulating process, the primary time constant estimator 30 generates the signal τ_1, representative of an estimate of the primary time constant in accord with the mathematical relationship:

$$\tau_1 = - \tau_f/\ln(1 - OVS) \quad (11)$$

The static gain estimation element, 34, generates a signal K_p, representing an estimate of the process's gain, in accord with the mathematical relation:

$$K_p = \delta c_1/(\delta m \cdot OVS) \quad (12)$$

The time required for the controlled variable signal, c, to reach the noise band, NB, is an exponential function of K_p and τ_1. The dead time estimator 28 generates a signal τ_d representative of the process dead time in accord with the expression

$$\tau_d = \tau_a + \tau_1 \ln(1 - NB/K_p \delta m) \quad (13)$$

If the self-regulating process under analysis is of the second order, the secondary lag rounds the peaks and shifts them to the right. It also reduces the areas A^+ and A^- (although maintaining their equality). Accordingly, for a second order self-regulating process, parameters K_p, t_1, and τ_2 cannot be determined directly, but must be estimated by approximation.

To begin, Equation (11) approximates the sum of τ_1 and τ_2:

$$\Sigma\tau = - \tau_f/\ln(1 - OVS) \quad (14)$$

Although, the accuracy of this decreases as t_1 approaches τ_2.

The ratio $A^+/\delta c_1$ is quite sensitiv to the ratio of τ_2/τ_1. Consequently, th ratio is first calculated as if th process w re first-order. To wit, the apparatus 20 determines th ratio in accord with th relation:

$$(A^+/\delta c_1)_1 = [\tau_a - \Sigma\tau \cdot \ln(1 + OVS)]/OVS \quad (15)$$

Using the result of that determination, a difference ratio signal δA is generated in accord with th relation:

$$\delta A = (A^+/\delta c_1) - (A^+/\delta c_1)_1 \quad (16)$$

The estimated ratio $R = \Sigma\tau/\tau_a$ is a function of the overshoot, OVS. The apparatus 20 determines a ratio signal R in accord with the expression

$$R = - 1/\ln(1 - OVS) \quad (17)$$

If R is greater than or equal to four, then the apparatus generates two correction factors CF_1 and CF_2 in accord with the mathematical relation

$$CF_1 = 1 + \delta A \cdot (0.78 \cdot \ln(R) - 1.06) \quad (18a)$$

$$CF_2 = 4 \cdot \delta A \cdot R^{-1.5} \quad (18b)$$

If R is less than four, then the apparatus performs the following steps to set the correction factor signals:

1) generate a signal, δA_{max}, as a function of the mathematical expression

$$\delta A_{max} = 0.051 \cdot e^{(0.82 \cdot R)}$$

2) if R less than or equal to two, generate a coefficient signal b having a value 0.5; otherwise, generate a coefficient signal, b, as a function of the mathematical expression

$$b = 0.4 + 0.38 \cdot \delta A_{max}$$

3) if δA is greater than or equal to δA_{max}, reset the correction factors signals CF_1 and CF_2 to values equal to the coefficient signal b;

4) otherwise, if δA is less than δA_{max}, generate the correction factors signals as functions of th mathematical expressions

$$CF_1 = b + (1 - b) \cdot \sqrt{1 - \delta A/\delta A_{max}} \quad (18c)$$

$$CF_2 = b \cdot (1 - \sqrt{1 - \delta A/\delta A_{max}}) \quad (18d)$$

From this, the primary time constant estimator 30 generates a signal τ_1 representative of the primary time constant of the second-order self-regulating process as follows:

$$\tau_1 = CF_1 \cdot \Sigma\tau \quad (19)$$

The second time constant estimator 32 generat s the signal τ_2 in accord with Eq. 22, below.

The steady state element 34, then generates the signal K_p, estimating the steady-state gain in accord with the expression

$$K_p = (\delta c_1/\delta m \cdot OVS) \cdot e^{1.3 \cdot \delta A} \quad (20)$$

Further, the element 28 generates the dead tim signal τ_d for 2nd-order non-self-regulating process s by executing the following steps:

i) estimating whether the secondary time constant τ_2 is substantially equal to the primary time constant τ_1 and, if so, generating a time interval t_2 as a function of the mathematical expression

$$t_2 = 1.65 \cdot \tau_1 \cdot \sqrt{NB/|K_p \cdot \delta m|}$$

ii) estimating whether said secondary time constant τ_2 is l ss than the primary time constant τ_1 and, if so, d termining the second time int rval t_2 iteratively in accord with th expression

$t_2 = -\tau_1 \bullet \ln\{[\tau_2 \bullet e^{-t_a/\tau_2} + (\tau_1 - \tau_2) \bullet (1 - NB/|K_p \bullet \delta m|)]/\tau_1\}$

iii) estimating the dead time, τ_d, as a function of the mathematical expression

$$\tau_d = \tau_a - t_2 \quad (21)$$

As noted above, the second time constant estimator 32 generates the signal τ_2 in accord with the mathematical relation:

$$\tau_2 = CF_2 \bullet \Sigma\tau \quad (22)$$

Summary

The foregoing describes methods and apparatus for determining characteristics of a process, such as primary and second time constants, dead-time, and gain, by applying a doublet pulse and measuring the process response. These methods and apparatus provide the simplicity, accuracy and effectiveness demanded by the art.

Those skilled in the art will appreciate that the illustrated embodiment is exemplary, and that other embodiments incorporating additions and modifications to that described above fall within the scope of the invention.

Claims

1. A method of testing a non-self-regulating process that

is controlled by application of a manipulated variable signal thereto to varying a first characteristic thereof, and that

generates a controlled variable signal representative of that first characteristic,

wherein, for determining a time constant of said process the method comprises the steps of:

A. applying a doublet pulse to said process by

i) incrementing said manipulated variable signal from an original value thereof a predetermined amount, δm, to cause said controlled variable signal to change from an original value thereof,

ii) monitoring said controlled variable signal to determine a time period, τ_a, after such incrementing that the controlled variable signal changes from its original value by a predetermined amount, NB,

iii) responding to such determination by decrementing said manipulated variable signal stepwise an amount substantially equal to, -2 x δm,

iv) incrementing, after another time interval, τ_a, said manipulated variabl signal substantially to said original value.

B. det rmining said time constant of said process as a function of a time-wis change in a value of said controlled variabl signal during application of said doublet pulse.

2. A method according to claim 1, wh rein said determining step includes the steps of

A. integrating a value of said controlled variable signal as a function of time during application of said doublet pulse to produce a valu A^+, and

B. estimating a primary time constant, τ_1, of said process as a function of the mathematical expression

$$\tau_1 = (\delta m \tau_a^2)/A^+.$$

3. A method according to claim 2, including the step of estimating a dead time, τ_d, of at least a select d non-self-regulating process as a function of th mathematical expression

$$\tau_d = \tau_a - (NB\tau_1/\delta m)$$

<u>and optionally</u> including the step of selecting a first-order non-self-regulating process to be one for which such dead time, τ_d, is to be estimated as a function of the mathematical expression

$$\tau_d = \tau_a - (NB\tau_1/\delta m),$$

<u>or optionally</u> including the steps of

A. determining a difference, δc, between the original value of the controlled variable signal and a value of that signal at a peak amplitude thereof during application of said doublet pulse,

B. identifying as a first-order non-self-regulating process one for which the time period, τ_a, is substantially equal to $A^+/\delta c$.

4. A method according to claim 2, including the steps of

A. determining a difference, δc, betwe n the original value of the controlled variable signal and a value of that signal at a peak amplitud thereof during application of said doublet pulse,

B. of estimating a secondary time constant, τ_2, of at least a selected non-self-regulating process as a function of the mathematical expression

$$\tau_2 = A^+/\delta c - \tau_a$$

<u>and optionally</u> including the step of selecting a second-order non-self-regulating process to be one for which such secondary time constant, τ_2, is to be s timated as a function of the mathematical expression

$$\tau_2 = A^+/\delta c - \tau_a$$

the method optionally further including the step of identifying as a second-order non-s lf-regulating process one for which the time period, τ_a, is n t substantially equal to $A^+/\delta c$.

5. A m thod according to claim 2, including the step of stimating the dead time, τ_d, of at least a selected non-self-regulating process by:

A. computing a first tim interval t_1 as a function of the mathematical expression

$$t_1 = NB * \tau_1/|\delta m|$$

B. initializing a s cond time interval t_2 to hav a value substantially equal to that of the first time interval, t_1,

C. interatively determining said second time interval t_2 in accord with the mathematical expression

$$t_2 = t_1 + \tau_2 * (1 - e^{-t_2/\tau_2})$$

until a difference between successive iterative values of said second time interval t_2 are within a predetermined range, and

where τ_2 is a secondary time constant of said selected non-self-regulating process,

D. estimating such dead time τ_d as a function of the expression

$$\tau_d = \tau_a - t_2$$

where t_2 is a final value resulting from said iteratively calculating step.

6. A method according to claim 5, including the step of selecting a second-order non-self-regulating process to be one for which such dead time, τ_d, is to be estimated as a function of the mathematical expression

$$\tau_d = \tau_a - t_2$$

and for example the method may further include the steps of

A. determining a difference, δc, between the original value of the controlled variable signal and a value of that signal at a peak amplitude thereof during application of said doublet pulse,

B. identifying as a second-order non-self-regulating process one for which the time period, τ_a, is not substantially equal to $A^*/\delta c$.

7. A method of testing a self-regulating process that is

controlled by application of a manipulated variable signal thereto to varying a first characteristic thereof, and that

generates a controlled variable signal representative of that first characteristic,

the improvement for determining a second characteristic of said process comprising the steps of:

A. applying a doublet pulse to said process by

i) incrementing said manipulated variable signal from an original value a predetermined amount, δm, to cause said controlled variable signal to change from an original value thereof,

ii) monitoring said controlled variable signal to d t rmin a tim period, τ_a, after such incr menting when the controlled variable signal chang s from original valu by a determined amount, NB,

iii) responding to such determination by decrementing said manipulated variabl signal stepwise an amount, -2 x δm,

iv) incrementing, after another tim interval τ_a, said manipulated variable signal to said original value.

B. determining said second characteristic of said process as a function of a time-wis change in a value of said controlled variable signal during application of said doublet pulse.

8. A method according to claim 7, wherein said determining step includes the steps of

A. identifying a first peak value, δc_1, representing a difference between the original value of the controlled variable signal and a value of that signal at a first peak amplitude thereof during application of said doublet pulse,

B. identifying a second peak value, δc_2, representing a difference between the original value of the controlled variable signal and th value of that signal at a second, subsequent peak amplitude thereof during application of said doublet pulse,

C. determining an overshoot ratio, OVS, of said process as a function of the mathematical expression

$$OVS = -\delta c_2/\delta c_1.$$

9. A method according to claim 8, wherein said determining step includes the step of estimating a primary time constant, τ_1, of at least a selected self-regulating process as a function of the mathematical expression

$$\tau_1 = -\tau_a/\ln(1 - OVS),$$

or said determining step includes the step of estimating a steady-state gain, K_p, of at least a selected self-regulating process as a function of the mathematical expression

$$K_p = \delta c_1/(\delta m * OVS),$$

or said determining step includes the steps of

A. estimating a steady state gain, K_p, of at least a selected self-regulating process as a function of the mathematical expression

$$K_p = \delta c_1/(\delta m * OVS)$$

B. estimating a dead time, τ_d, of that process as a function of the mathematical expression

$$\tau_d = \tau_a + \tau_1 * \ln(1 - NB/K_p * \delta m)),$$

the selected self-regulating process in ach case for example being a first-order self-regulating process.

10. A method according to claim 8, wherein said determining step includes the step of executing the following op rations for at l ast a selected self-regulating proc ss, which for instance is a second-order-self-regulating process:

A. estimating a total tim lag, $\Sigma\tau$, as a function

of the mathematical expression

$$\Sigma\tau = -\tau_a/\ln(1 - OVS)$$

B. integrating a valu of said controlled variable signal as a function of time, during a period when that variable signal exceeds its original value and during application of said doublet pulse, to produce a value A^+,

C. computing a first ratio, $(A^+/\delta c_1)_1$, as a function of the mathematical expression

$$(A^+/\delta c_1)_1 = [\tau_a - (\Sigma\tau * \ln(1 + OVS))]/OVS$$

D. computing a difference between ratios, δA, as a function of the mathematical expression

$$\delta A = (A^+/\delta c_1) - (A^+/\delta c_1)_1$$

E. computing a second ratio, R, as a function of the mathematical expression

$$R = -1/\ln(1 - OVS)$$

F. responding to a value of R greater than or equal to 4 for generating correction factors CF_1 and CF_2 as functions of the mathematical expressions

$$CF_1 = 1 + \delta A * (0.78 * \ln(R) - 1.06)$$

$$CF_2 = 4 * \delta A * R^{-1.5}$$

G. responding to a value of R less than 4 for

i) determining a maximum estimate of δA, namely δA_{max}, as a function of the mathematical expression

$$\delta A_{max} = 0.051 * e^{(0.82 \cdot R)}$$

ii) responding to a value of R less than or equal to 2 for defining a coefficient b to a value of 0.5, and responding to a value of R greater than 2 for defining said coefficient, b, as a function of the mathematical expression, otherwise giving b the value

$$b = 0.4 + 0.38 * \delta A_{max}$$

iii) responding to a value of δA being greater than or equal to δA_{max} for generating correction factors CF_1 and CF_2 as equal to coefficient b, and for otherwise estimating these correction factors as a function of the mathematical expression

$$CF_1 = b + (1 - b) * \sqrt{1 - \delta A/\delta A_{max}}$$

$$CF_2 = b * (1 - \sqrt{1 - \delta A/\delta A_{max}})$$

H. estimating said primary time constant τ_1 according to the mathematical expression

$$\tau_1 = CF_1 * \Sigma\tau.$$

11. A method according to claim 8, wherein said determining step includes the step of executing the following operations for at least a selected self-regulating process, which for instance is a second-order self-regulating process:

A. generating a summation signal, $\Sigma\tau$, as a function of the mathematical expression

$$\Sigma\tau = -\tau_a/\ln(1 - OVS)$$

B. integrating a value of said controlled variable signal as a function of time, during a period wh n that variable signal exce ds its original value, during application of said doublet pulse to produce a value A^+,

C. computing a first rati , $(A^+/\delta c_1)_1$, as a function of the mathematical expression

$$(A^+/\delta c_1)_1 = [\tau_a - (\Sigma\tau * \ln(1 + OVS))]/OVS$$

D. computing a difference δA of ratios as a function of the mathematical expression

$$\delta A = (A^+/\delta c_1) - (A^+/\delta c_1)_1$$

E. computing said steady-state gain K_p as a function of the mathematical expression

$$K_p = (\delta c_1/(\delta m * OVS)) * e^{1.3} \cdot \delta A$$

12. A method according to claim 10, wherein said executing step includes the step of estimating a secondary time constant, τ_2, as a function of th mathematical expression

$$\tau_2 = CF_2 * \Sigma\tau, \text{ and}$$

for example, the method further includes the step f estimating a dead time, τ_d, of at least a self-regulating process, for example a second-order self-regulating process, having a secondary time constant τ_2, said estimating step comprising the steps of:

A. estimating whether said secondary time constant τ_2 is substantially equal to said primary time constant τ_1, and responding to such estimation for determining a value for a time interval t_2 as a function of the mathematical expression

$$t_2 = 1.65 * \tau_1 * \sqrt{NB/|K_p * \delta m|}$$

B. estimating whether said secondary time constant τ_2 is not substantially equal to said primary time constant τ_1 for determining a value for said time interval t_2 iteratively, until it n longer changes significantly, as a function of the mathematical expression

$$t_2 = -\tau_1 * \ln\{[\tau_2 * e^{-t_2/\tau_2} + (\tau_1 - \tau_2) * (1 - NB/|K_p * \delta m|)]/\tau_1\}$$

C. estimating a dead time, τ_d, as a function of the mathematical expression

$$\tau_d = \tau_a - t_2$$

13. An apparatus for testing a process that is controlled by application of a manipulated variable signal thereto to varying a first characteristic thereof, and that generates a controlled variable signal representative of that first characteristic, said apparatus comprising:

A. pulse means, coupled with said process, for generating a manipulated variable signal representative of a doublet pulse and for applying that signal to said process,

B. monitoring means, coupled with said process, for monitoring said controlled variabl signal,

C. analysis m ans, coupl d to said monitoring m ans, for determining a second characteris-

tic of said process as a function of a time-wise change in said controlled variable signal during application of said doubl t pulse.

14. An apparatus according t claim 13, wherein said pulse means includes
A. means for incrementing said manipulated variable signal from an original value thereof a predetermined amount, δm, to cause said controlled variable signal to change from an original value thereof,
B. means coupled to said monitoring means for determining a time period, τ_a, after such incrementing that the controlled variable signal changes from its original value by a predetermined amount, NB,
C. means for decrementing said manipulated variable signal, after said time period τ_a, stepwise an amount substantially equal to, -2 x δm, and for incrementing, after another time interval, τ_a, said manipulated variable signal substantially to said original value.

15. An apparatus according to claim 13, wherein said analysis means includes
A. means for integrating a value of said controlled variable signal as a function of time during application of said doublet pulse to determine a value A^+, and for generating a signal representative thereof, and
B. primary time constant means for generating a signal representative of a primary time constant, τ_1, of said process in accord with the mathematical expression

$$\tau_1 = (\delta m \tau_a^2)/A^+ .$$

the apparatus, <u>for example</u>, including means for generating a signal representative of a dead time, τ_d, of at least a selected process, wherein that signal is generated in accord with the mathematical expression

$$\tau_d = \tau_a - (NB\tau_1/\delta m),$$

and <u>optionally</u> further including means for selecting a first-order non-self-regulating process to be one for which such dead time, τ_d, is to be estimated in accord with the mathematical expression

$$\tau_d = \tau_a - (NB\tau_1/\delta m)$$

16. An apparatus according to claim 15, including
A. means for determining a difference, δc, between the original value of the controlled variable signal and a value of that signal at a peak amplitude thereof during application of said doublet pulse,
B. means for determining whether the time period, τ_a, is substantially equal to factor $A^+/\delta c$,
C. means responsive to an affirmativ such determinati n for id ntifying the corr sponding process as b ing of th first ord r.

17. An apparatus according to claim 15, including
A. means for generating a signal, δc, representative of a difference between the original value of the controlled variable signal and a value of that signal at a peak amplitude thereof during application of said doublet pulse,
B. secondary time constant means for generating a signal representative of a secondary time constant, τ_2, of at least a selected non-self-regulating process, said signal being generated in accord with the mathematical expression

$$\tau_2 = A^+/\delta c - \tau_a ,$$

the apparatus, <u>for example</u>, further including means for selecting a second-order non-self-regulating process to be one for which such secondary time constant, τ_2, is to be estimated in accord with the mathematical expression

$$\tau_2 = A^+/\delta c - \tau_a ,$$

and <u>optionally</u> further including means identifying as a second-order non-self-regulating process one for which the time period, τ_a, is not substantially equal to $A^+/\delta c$.

18. An apparatus according to claim 15, including dead time means for generating a signal representative of a dead time, τ_d, of at least a selected process, said dead time means including:
A. means for generating a signal representative of a first time interval t_1 in accord with the mathematical expression

$$t_1 = NB * \tau_1/|\delta m|$$

B. means for generating a signal representative of a second time interval t_2 to have a value substantially equal to that of the first tim interval, t_1,
C. means for iteratively regenerating the signal representative of said second time int rval t_2 in accord with the mathematical expression

$$t_2 = t_1 + \tau_2 * (1 - e^{-t_2/\tau_2})$$

until a difference between successive iterative values of said second time interval t_2 are within a predetermined range, and
where τ_2 is a secondary time constant of said selected non-self-regulating process,
D. means for generating a signal representative of such dead time τ_d in accord with the expression

$$\tau_d = \tau_a - t_2$$

where t_2 is a final value resulting from said iteratively calculating step.

19. An apparatus according to claim 18, wher in said secondary time constant means includes means

for sel cting a second-order non-s lf-regulating process to be on for which such d ad tim , τ_d, is to be estimated in accord with the mathematical expression

$$\tau_d = \tau_a - t_2$$

and, for example, said secondary time constant means includes

A. means for generating a signal, δc, representative of a difference between the original value of the controlled variable signal and a value of that signal at a peak amplitude thereof during application of said doublet pulse,

B. means identifying as a second-order non-self-regulating process one for which the time period, τ_a, is not substantially equal to $A^+/\delta c$.

20. An apparatus of testing a self-regulating process that is

controlled by application of a manipulated variable signal thereto to varying a first characteristic thereof, and that

generates a controlled variable signal representative of that first characteristic,

said apparatus comprising:

A. pulse means, coupled with said process, for generating a manipulated variable signal representative of a doublet pulse and for applying that signal to said process,

B. monitoring means, coupled with said process, for monitoring said controlled variable signal,

C. analysis means, coupled to said monitoring means, for determining a second characteristic of said process as a function of a time-wise change in said controlled variable signal during application of said doublet pulse.

21. An apparatus according to claim 20, wherein said pulse means includes

A. means for incrementing said manipulated variable signal from an original value thereof a predetermined amount, δm, to cause said controlled variable signal to change from an original value thereof,

B. means coupled to said monitoring means for determining a time period, τ_a, after such incrementing that the controlled variable signal changes from its original value by a predetermined amount, NB,

C. means for decrementing said manipulated variable signal, after said time period τ_a, stepwise an amount substantially equal to, -2 x δm, and for incrementing, after another time interval, τ_a, said manipulated variable signal substantially to said original valu .

22. An apparatus according to claim 20, wherein said analysis means includes

A. id ntifying a first peak value, δc_1, representing a difference b tw en the original value of th controlled variable signal and a valu of that signal at a first peak amplitud thereof during application of said doublet pulse,

B. identifying a second peak value, δc_2, representing a difference between the original value of the controlled variable signal and the value of that signal at a second, subsequent peak amplitude thereof during application of said doublet pulse,

C. determining an overshoot ratio, OVS, of said process in accord with the mathematical expression

$$OVS = -\delta c_2/\delta c_1,$$

and optionally said analysis means includes primary time constant means for generating a signal representative of an estimate of a primary time constant τ_1, of at least a selected self-regulating process, for instance a first-order self-regulating process, said signal being generated in accord with the mathematical expression

$$\tau_1 = -\tau_a/\ln(1 - OVS),$$

and still further said analysis means may include steady-state gain means for generating a signal, K_p, representative of a steady-state gain of at least a selected self-regulating process, for example a first-order self-regulating process, said signal being generated in accord with the mathematical expression

$$K_p = \delta c_1/(\delta m \cdot OVS).$$

23. An apparatus according to claim 22, wherein said analysis means includes

A. steady state gain means for generating a signal, Kp, representative of a steady state gain of at least a selected self-regulating process such as a first order self-regulating process, said signal being generated in accord with the mathematical expression

$$K_p = \delta c_1/(\delta m \cdot OVS)$$

B. dead time means for generating a signal, τ_d, representative of a dead time of that process, said signal being generated in accord with the mathematical expression

$$\tau_d = \tau_a + \tau_1 \cdot \ln(1 - NB/(K_p \cdot \delta m))$$

24. An apparatus according to claim 22, wherein said analysis means includes means for executing th following operations for at least a selected self-regulating process, which for example is a second-order self-regulating process:

A. generating a signal, $\Sigma\tau$, representative of a total time lag in accord with the mathematical expression

$$\Sigma\tau = -\tau_a/\ln(1 - OVS)$$

B. g nerating a signal, A^+, representativ of an

integration of a value of said controlled variabl signal as a function of time, during a period when that variable signal exceeds its original value and during application of said doublet pulse,,

C. generating a signal, $(A^+/\delta c_1)_1$, in accord with the mathematical expression

$$(A^+/\delta c_1)_1 = [\tau_a - (\Sigma\tau \cdot \ln(1 + OVS))]/OVS$$

D. generating a signal, δA, in accord with the mathematical expression

$$\delta A = (A^+/\delta c_1) - (A^+/\delta c_1)_1$$

E. generating a signal, R, in accord with the mathematical expression

$$R = -1/\ln(1 - OVS)$$

F. responding to a value of R greater than or equal to 4 for generating correction factor signals CF_1 and CF_2 in accord the mathematical expressions

$$CF_1 = 1 + \delta A \cdot (0.78 \cdot \ln(R) - 1.06)$$

$$CF_2 = 4 \cdot \delta A \cdot R^{-1.5}$$

G. responding to a value of R less than 4 for

i) generating a signal, δA_{max}, in accord with the mathematical expression

$$\delta A_{max} = 0.051 \cdot e^{(0.82 \cdot R)}$$

ii) responding to a value of R less than or equal to 2 for generating a coefficient signal, b, to having a value of 0.5, and responding to a value of R greater than 2 for generating said coefficient signal, b, in accord with the mathematical expression

$$b = 0.4 + 0.38 \cdot \delta A_{max}$$

iii) responding to a value of δA being greater than or equal to δA_{max} for generating correction factor signals CF_1 and CF_2 as equal to said coefficient signal b, and for responding to a value of δA being less δA_{max} for generating these correction factor signals in accord with the mathematical expression

$$CF_1 = b + (1 - b) \cdot \sqrt{1 - \delta A/\delta A_{max}}$$

$$CF_2 = b \cdot (1 - \sqrt{1 - \delta A/\delta A_{max}})$$

H. generating a primary time constant τ_1 in accord with the mathematical expression

$$\tau_1 = CF_1 \cdot \Sigma\tau.$$

25. An apparatus according to claim 22, wherein said analysis means includes means for executing the following operations for at least a selected self-regulating process, such as a second-order self-regulating process:

A. generating a summation signal, $\Sigma\tau$, in accord with the mathematical expression

$$\Sigma\tau = -\tau_a/\ln(1 - OVS)$$

B. generating a signal A^+ representative of an integration of a value of said controll d variable signal as a function of time, during a p riod when that variable signal exceeds its original value, during application of said doubl t pulse to produce a value A^+,

C. generating a first rati signal, $(A^+/\delta c_1)$, in accord with the mathematical expression

$$(A^+/\delta c_1)_1 = [\tau_a - (\Sigma\tau \cdot \ln(1 + OVS))]/OVS$$

D. generating a difference of ratios signal δA in accord with the mathematical expression

$$\delta A = (A^+/\delta c_1) - (A^+/\delta c_1)_1$$

E. generating a steady-state gain signal K_p in accord with the mathematical expression

$$K_p = (\delta c_1/(\delta m \cdot OVS)) \cdot e^{1.3} \cdot \delta A,$$

the apparatus optionally including means for estimating a secondary time constant, τ_2, in accord with the mathematical expression

$$\tau_2 = CF_2 \cdot \Sigma\tau,$$

and the apparatus for example comprising means for generating a dead time signal, τ_d, of at least a self-regulating process, e.g. a second-order self-regulating process, having a secondary time constant τ_2, by executing th following operations.

I. estimating whether said secondary tim constant τ_2 is substantially equal to or greater than said primary time constant τ_1, and responding to such estimation for determining a value for a time interval t_2 in accord with the mathematical expression

$$t_2 = 1.65 \cdot \tau_1 \cdot \sqrt{NB/|K_p \cdot \delta m|}$$

II. estimating whether said secondary time constant τ_2 is not substantially equal to or greater than said primary time constant τ_1 for determining a value for said time interval t_2 iteratively, until it no longer changes significantly, in accord with the mathematical expression

$$t_2 = -\tau_1 \cdot \ln\{[\tau_2 \cdot e^{-t_2/\tau_2} + (\tau_1 - \tau_2) \cdot (1 - NB/|Kp \cdot \delta m|)]/\tau_1\}$$

III. generating said dead time signal, τ_d, in accord with the mathematical expression

$$\tau_d = \tau_a - t_2$$

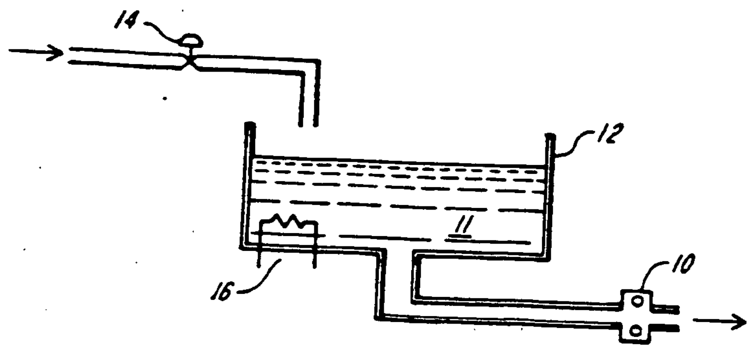


FIG. 1A

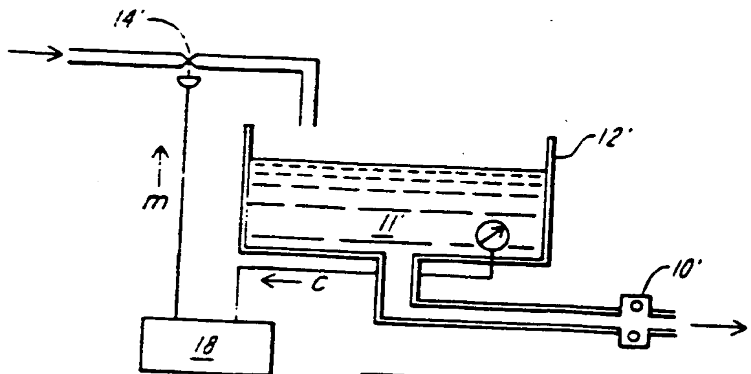


FIG. 1B

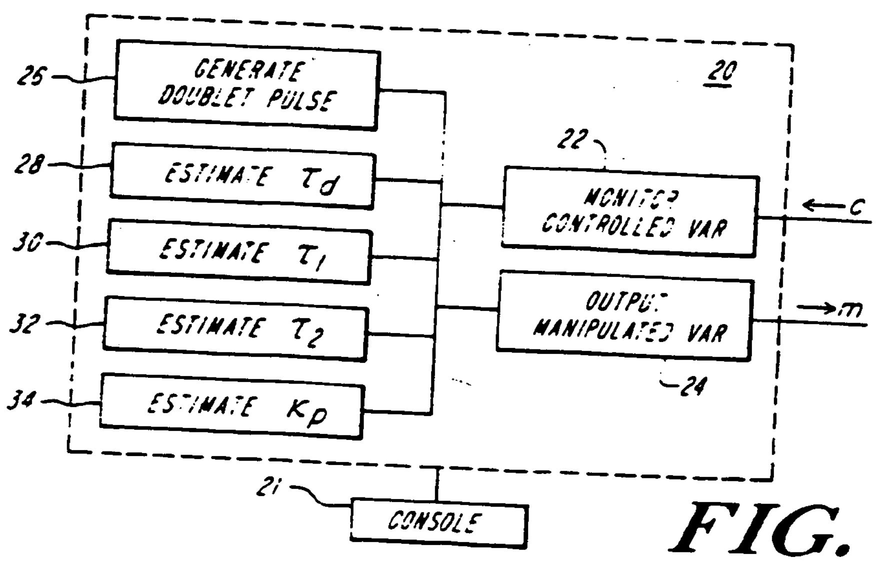
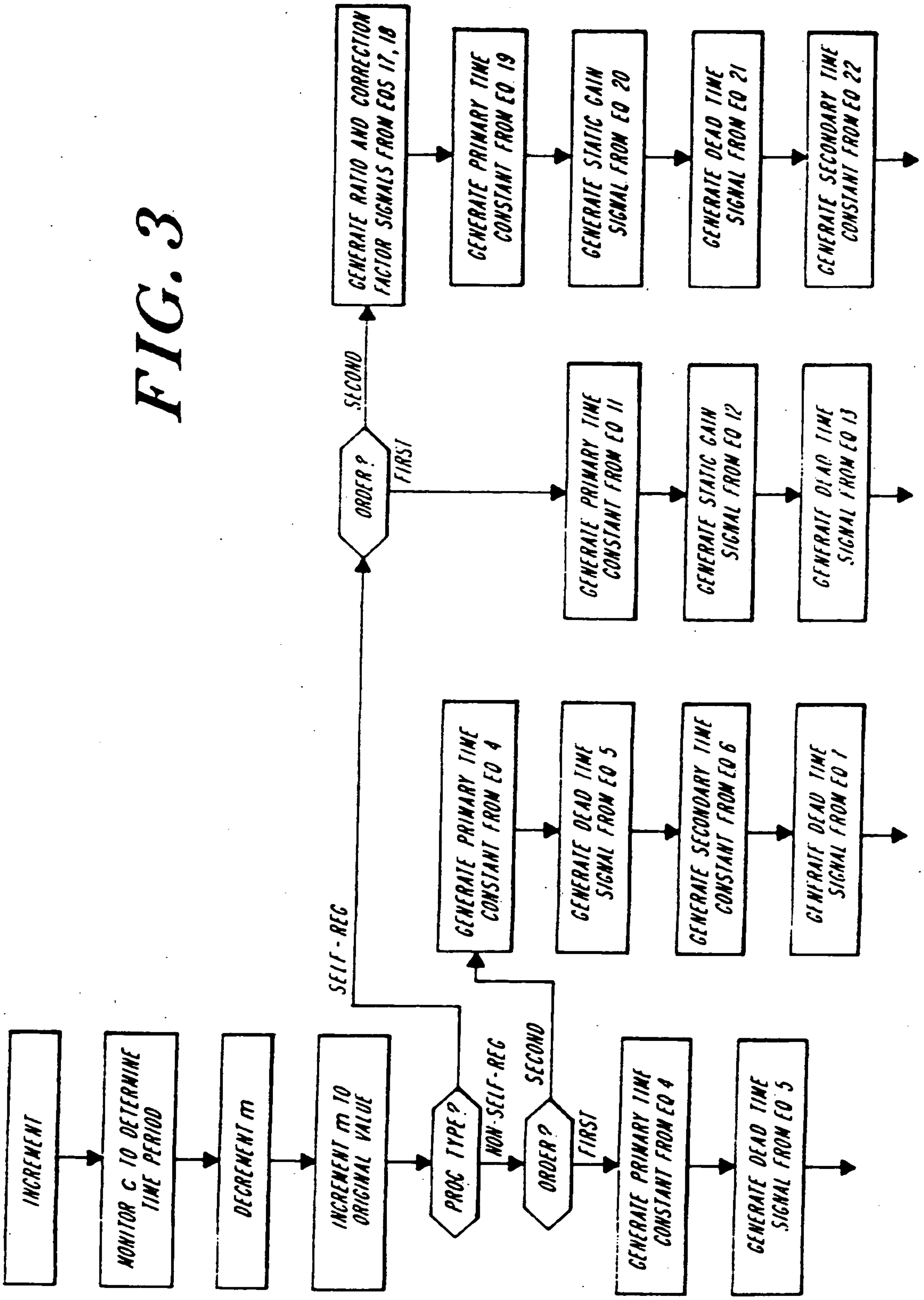


FIG. 2

FIG. 3


INCREMENT
MONITOR c TO DETERMINE TIME PERIOD
DECREMENT m
INCREMENT m TO ORIGINAL VALUE
PROC TYPE?
NON-SELF-REG
ORDER?
FIRST
GENERATE PRIMARY TIME CONSTANT FROM EQ 4
GENERATE DEAD TIME SIGNAL FROM EQ 5
SECOND
GENERATE PRIMARY TIME CONSTANT FROM EQ 4
GENERATE DEAD TIME SIGNAL FROM EQ 5
GENERATE SECONDARY TIME CONSTANT FROM EQ 6
GENERATE DEAD TIME SIGNAL FROM EQ 7
SELF-REG
ORDER?
FIRST
GENERATE PRIMARY TIME CONSTANT FROM EQ 11
GENERATE STATIC GAIN SIGNAL FROM EQ 12
GENERATE DEAD TIME SIGNAL FROM EQ 13
SECOND
GENERATE RATIO AND CORRECTION FACTOR SIGNALS FROM EQS 17, 18
GENERATE PRIMARY TIME CONSTANT FROM EQ 19
GENERATE STATIC GAIN SIGNAL FROM EQ 20
GENERATE DEAD TIME SIGNAL FROM EQ 21
GENERATE SECONDARY TIME CONSTANT FROM EQ 22

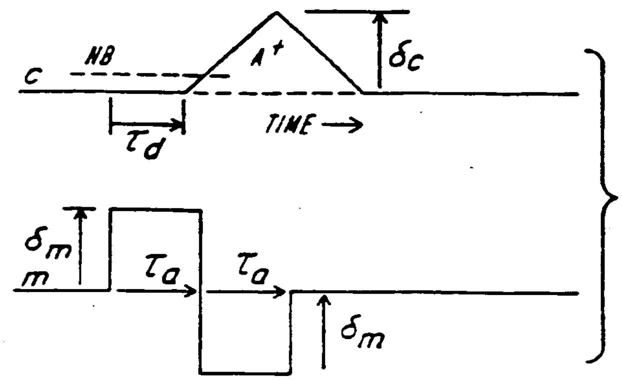


FIG. 4

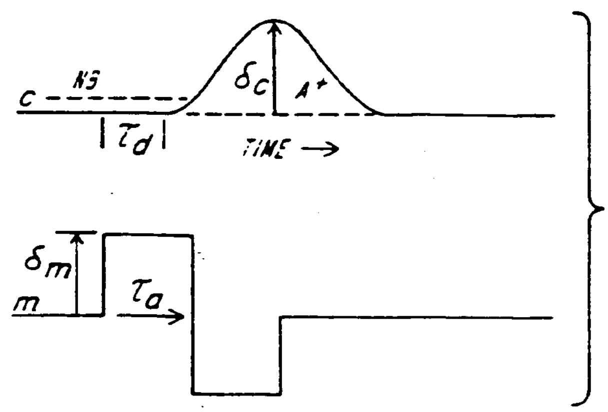


FIG. 5

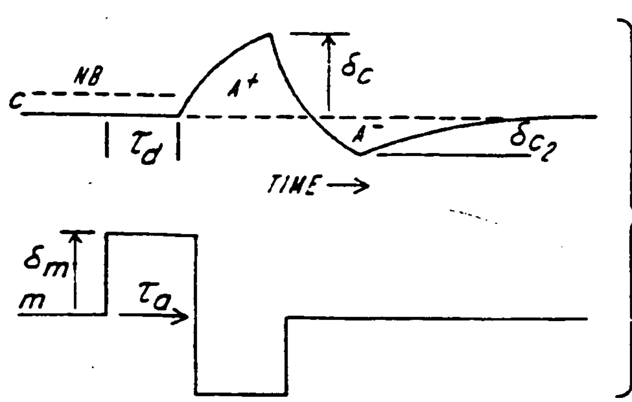


FIG. 6

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(54) Method and apparatus for analyzing process characteristics.

(57) Methods and apparatus for determining characteristics of a process -- such as primary and second time constants, dead-time, and gain -- apply a doublet pulse to the process and measure its response. By way of example, in one aspect there is provided a method for generating a signal, τ_1, representing an estimate of a primary time constant of a non-self-regulating process, in accord with the mathematical expression τ_1 $(\delta m \tau_a^2)/A^+$; where A^+ is a factor representing the time-wise integration of the controlled variable during the period when the doublet pulse is being applied.

EP 0 572 245 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 93304099.0

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	US - A - 4 094 959 (BALL et al.) * Abstract; claims 1-6 * --	1,13, 20,21	G 05 B 23/00
A	EP - A - 0 190 644 (FUJI) * Fig. 1; claims 1-4 * ----	1,11, 22,23	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			G 05 B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	30-06-1995	FUSSY

CATEGORY OF CITED DOCUMENTS

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